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Minutes of Workshop on Gaseous Dielectrics for Use in Future Electric-Power Systems

Richard J. Van Brunt

Electrosystems Division
Center for Electronics
    and Electrical Engineering
National Bureau of Standards

September 10-11, 1979

Issued January 1980

Final Report

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Introduction

This workshop was held at the National Bureau of Standards laboratories in Gaithersburg, Maryland, on September 10-11, 1979. The agenda and a list of active participants is attached. The workshop was organized for the purpose of addressing questions concerning current and planned research on development of new gaseous dielectrics viewed as possible substitutes for SF_6. Focus was on identifying technological barriers to use of new gases and gas mixtures and questions concerning properties of gases in need of further investigation. It brought together many individuals from industry, government, and academia with diverse interests and opinions concerning the needs for future research in the gaseous dielectrics area. It was assumed that the workshop would provide a stimulating prelude to the forthcoming International Symposium on Gaseous Dielectrics where unresolved questions concerning the needs and desirable directions of future research can again be debated.

Editors Comments

This document has been prepared primarily to serve the purpose of a record for the benefit of those who participated in the Gaseous Dielectrics Workshop. The minutes presented here were extracted from tape recordings made during all sessions of the workshop. This is not a verbatim transcription. The recordings of formal talks, discussions, and comments have been edited and in some cases reordered and paraphrased

for the sake of coherence and clarity. Where possible, individual

speakers and their affiliations have been identified. No attempt

was made to transcribe conversations in those few cases where voice

recording was undecipherable or where intended meaning was unclear.

It is hoped, however, that all major points are covered herein. The

editor apologizes in advance for any misinterpretations or misplaced

emphasis. The actual tapes used to prepare these minutes are on file

at the National Bureau of Standards, Washington, D.C. 20234. Copies

of these minutes have been distributed to all active participants in

the workshop as indicated on the attached list.

Minutes

September 10, 1979 - T. F. Garrity, Chairman

I. 1:00 p.m. - Chairman's Opening Comments, T. F. Garrity,

Department of Energy

Concern was expressed that those engaged in research on

"improved" gaseous dielectrics should be working toward common

objectives. There should be mutual understanding among researchers

in this field about what is meant by a "good" or "improved" gas

dielectric. One purpose of the workshop was to place in perspective

the research currently carried out under EPRI and DOE sponsorship

on development of new gaseous dielectrics. It was noted that there

are several criteria to be considered in deciding what is meant by

an improved dielectric and these include: (1) cost of gas,

(2) performance, and (3) system requirements. It was pointed out,

as an example, that the cost of gas could be as much as three times

presently used SF_6, but total system cost could be reduced by 20% with improved dielectric performance, so that mere cost of gas has to be tempered by overall system demands.

Questions to be considered are the following: Can performance of currently used SF_6 be improved so as to make better use of its inherent capabilities? What are we designing the gases for? Are we, for example, designing these gases for meeting lightning impulse requirements, switching impulse requirements, resistance to particles and contamination, temperature and heat transfer requirements, or 60-Hz withstand voltage? Which of these criteria is the most important in a given application? It is clear that one must take a look at the total system in deciding these issues.

It was argued that it is not the purpose of this meeting to come away with a precise definition of what is meant by a gaseous dielectric superior to SF_6. It is rather intended that this meeting should instill ideas and raise questions which will enable those actively involved in research to work toward the same basic objectives. This workshop might be considered the first step in answering the important question concerning what is meant by a superior gaseous dielectric. Hopefully, it will lead to a better, more intelligent discussion of this subject at the next International Symposium on Gaseous Dielectrics. The need was expressed for a two-way exchange between industry on the one hand and research establishments on the other in development of new gaseous dielectrics.

II. 1:15 p.m. - D. E. Massey, GPU Service Corporation,

Users Look at Insulation Systems

Those at the workshop were reminded that the utility's objective is to provide power at the lowest cost possible. This, however, is becoming increasingly difficult with increasing fuel costs and incidental costs at generating stations as required, for example, to meet environmental standards. In considering costs of a 500 kV transmission line, it was noted that normal operating capacity of a line is only 50% of maximum design capacity. On a cost basis, overhead transmission lines still win out over underground lines, except where there are corridor limitations or restrictions.

For a compressed gas system, the cost of gas is not necessarily a significant consideration. It was noted, for example, that in a transmission system, if one had a gas that could improve the dielectric strength of SF_6 by 100%, then one could afford to use that gas at five times the cost of SF_6 because of the resulting reduction in the sheath cost corresponding to its reduction in size. It was mentioned that 44% of the overall cost is associated with the sheath.

In discussing transmission costs, it was noted that the reactive losses in an SF_6 system are high. Maintenance costs for SF_6 lines are also considerably higher than for comparable overhead lines. If failure occurs, underground lines are out of operation for longer times than overhead lines, weeks compared to hours. The maintenance downtime for a line is a significant cost consideration.

It was noted for circuit breakers that the gas used has a high handling cost compared to oil because of the stringent purity (cleanliness) requirements. The need was thus expressed for developing simplified gas handling methods which can be dealt with either by improving properties of the gaseous medium so that it is less susceptible to contamination or by improving the method, e.g., the gas handling equipment and procedures. It was emphasized that gas requirements in breakers are different from those in transmission lines and other substation equipment. There is no reason for a single gas in a breaker. It has been found that H_2 is very good as an interrupting medium even though it is not particularly good as an insulant afterwards.

Concerning substations, it was indicated that the objective here is size reduction to be achieved by increasing the dielectric strength of the insulating medium. Again cost of the insulating gas need not be a major consideration. It is always the overall owning cost that is significant.

Questions:

Dr. N. Grao Trinh of Hydro-Quebec added to the presentation by pointing out the gap that exists between the theoretical and practical limits on compressed gas insulated (CGI) system size reduction. At the Hydro-Quebec research laboratories, they are looking at CGI bus system performance improvement. Associated with this, there is the problem of reducing the size of a conductor for a given current capacity as well as the problem of increasing operating temperature particularly for the insulating spacers. In dealing with the problem

of corona onset, one must take into consideration the onset field gradient for different size conductors.

Tom Garrity of DOE mentioned that it had been pointed out to him by people at AEP that the cost of maintenance on their four compressed gas insulated substations had recently gone down to about a third of that for comparable open air substations.

Loucas Christophorou of ORNL asked how cost would depend on gas pressure. The reply was that this is not a significant consideration, i.e., the cost figures presented in the talk do not change significantly with operating gas pressure provided pressures are not excessively high.

The question was raised about how the utilities feel about the issue of toxicity, and it was made clear that they do not want to use anything that is toxic. For one thing, the handling costs of toxic fluids is too high.

III. 1:30 p.m. - R. E. Wootton, Westinghouse R&D Center,

       <u>An Experimental Study of Dielectric Gases for</u>

       <u>Practical Applications</u>

The discussion in this talk centered around results obtained as part of an EPRI-sponsored project that was recently carried out with the cooperation of E. I. du Pont de Nemours and Company. A final report on this work is now in preparation. In this project, they looked at a variety of gases from both the insulation and interruption point of view.

It was noted that many aspects of the gas must be considered in determining whether or not it has any clear superiority or advantages

over commonly used SF_6. These aspects include (1) electric strength,
(2) carbonization, (3) vapor pressure, (4) toxicity, (5) environmental
acceptability, (6) immunity to adverse effects of moisture, contamination,
and particles, (7) stability and overall compatibility with other likely
components of the system. They did not conduct practical laboratory
work on all of these aspects, although this may be needed to determine
ultimate suitability of gases as useful dielectrics. They did
laboratory measurements on: (1) breakdown (dielectric strength),
(2) carbonization, and (3) stability and compatibility with materials
of construction. They carried out a comprehensive literature survey
and did calculations on the problem of vapor pressure determination,
and also did a literature survey on toxicity. Some cost analysis
was done although difficulties and uncertainties remain on this
question. Excluded from the work scope were the influence of
humidity, moisture, contamination and particles.

Examples were given of the types of data obtained. They, for
example, looked at molecular weight dependence of relevant electrical
and physical properties, e.g., breakdown, vapor pressure.
Generally as molecular weight goes up, breakdown strength of the gas
goes up and vapor pressure goes down. They also correlated dielectric
strength with heat of atomization and boiling point.

They tried to formulate rules based on vapor pressure, electric
strength, etc., for selecting and screening gases for further study.
They considered thirty pure gases as well as mixtures with SF_6.
Measurements of electrical breakdown strength were performed in
quasi-uniform fields using sphere-sphere electrodes and 60-Hz voltage.

Of the thirty pure gases examined, some had higher dielectric strengths than SF_6.

Consideration was given to dependence of breakdown strength on temperature. The maximum dielectric strength that can be achieved with any gas at a particular temperature is limited by its vapor pressure. In general, maximum dielectric strength increases rapidly with increasing temperature due to increased vaporization. To determine if a gas is indeed superior in performance to SF_6, one must decide on the temperature range of interest. In any application, the best choice of gas depends on operating temperature range. It was pointed out as an example that CF_3SF_5 has a higher dielectric strength than pure SF_6 at higher temperatures for a gas pressure limited to 400 kPa.

Some of the gas mixtures examined included: $CBrF_3+SF_6$, $CClF_3+SF_6$, $CF_3SF_5+SF_6$, $CF_3SO_2F+SF_6$, and $CF_2=CClF+SF_6$. They measured dependence of breakdown in a quasi-uniform field on gas mixture ratios and usually found a linear relationship. Some of these mixtures show promise and are perhaps worthy of additional consideration. The gas CF_3SO_2F was noted as an example to have a dielectric strength considerably higher than SF_6 and exhibit a linear relationship in mixtures with SF_6; also, it does not carbonize and is believed to be nontoxic.

In some cases, nonlinear mixture characteristics were observed. In a few mixtures, such as the $CF_3CF=CF_2+SF_6$ mixture, a synergistic effect was observed, i.e., the breakdown strength of the mixture was higher than either of the constituents. This effect was observed in sphere-sphere and sphere-plane electrode systems and it was discovered

that the degree of synergism appears to be enhanced with increasing field uniformity. It was noted that the simple linear, weighting formula for predicting net ionization and attachment coefficients in the gas, although explaining some nonlinear characteristics, cannot be applied to explain this synergistic effect.

The importance of vapor pressure was again emphasized. They considered two minimum operating temperatures, namely 0 °C and -30 °C. The latter was found to be too restrictive on the gases that could be used. However, all gases and mixtures considered could be operated without condensation down to 0 °C. For mixtures, this condition puts a limit on the mixture ratios that can be used. Most of the stronger dielectric gases do not exert as high a vapor pressure as SF_6. In considering, for example, the tertiary mixture $0.44SF_6+0.06CF_3SF_5+0.50N_2$, the 6% CF_3SF_5 indicated is the maximum amount of that gas that can be added without condensation at -30 °C.

Carbonization was pointed out as an important problem from a practical point of view. Some gases such as $CF_3-C\equiv C-CF_3$ that initially have dielectric strengths greater than SF_6 show marked decline in breakdown strength after a breakdown has occurred. In the case of $CF_3-C\equiv C-CF_3$, large carbon deposits are left on the electrodes after several breakdowns, and these may eventually build up to the extent that they bridge the electrode gap. A computer model of the carbonization process was described which uses information on the heats of formation and latent heats of the material to predict the decomposition modes at high temperatures ($\sim$ 1000 °K). Among the molecules

formed is elemental carbon, and the model predicts the amount of carbon formation as a function of temperature. The degree of carbonization as predicted by the model decreases with addition of SF_6 to the gas. The explanation for this is that the carbon is absorbed in the formation of gaseous compounds such as CF_4. An extreme example of this is a mixture of CF_4+SF_6 which was found to give no carbon formation at any temperature. They verified the effect of SF_6 on suppressing carbonization in arcing experiments in which decomposition products were collected. They report that the degree of carbonization generally decreases with increasing SF_6 concentration, often up to a sharp cut-off point beyond which there is no carbonization.

The problem of high temperature aging was also examined. Here it was noted that one must not only look at the stability of the gas but also at what the gas or its decomposition products do to the solid insulation system. Aging was studied by monitoring gas pressure as a function of temperature and by analyzing the gas by gas chromatography and other methods. They also looked at the effect of various gases on deterioration of resins.

The question of cost was difficult to answer because costs depend on volume of production which depends on volume of use, environmental restrictions, etc. In general, however, gas costs go down with decreasing dielectric strength. To get a dielectric strength higher than SF_6 one must pay a higher price.

Concerning needs for future research it was suggested that long-time-to-breakdwon studies should be undertaken. The reasons why one cannot attain, in practical systems, more than 50% of the intrinsic

strength of SF_6 need to be examined. Is this limitation due to dust and particles or surface roughness? It was also recommended that emphasis be put on the study of synergistic effects in gas mixtures.

In conclusion, it was noted that according to this study no single, pure gas has been found that is "superior" to SF_6 in all respects. On the other hand, some mixtures may be superior to SF_6 in limited respects, e.g., they have lower cost, wider operating temperature, immunity to particles, etc. Such mixtures may show promise for future applications. The promising gases considered in this project need to be examined further to determine their resistance to adverse effects of particles and dust.

Questions:

Dr. Mastroianni of Allied Chemical commented that they had observed breakdown with SF_6-fluorocarbon mixtures in the laboratory using sphere-plane geometry that had as much as 18% improvement over SF_6, but showed no such improvement in an actual test section of bus line.

A question was raised about the field configuration dependence of the breakdown results. It was again emphasized that synergism was observed in only three gas mixtures and the effect becomes enhanced as the field becomes more uniform.

IV. 2:00 p.m. - M. J. Mastroianni, Allied Chemical Corporation,
            Breakdown and Stability Properties of Some New
            Gaseous Dielectrics

The program described was twofold in which they looked at:
(1) dielectric strengths of potentially new dielectrics and (2) arc

stability. Concern was expressed about the acceptability of gas
mixtures by the utilities, in particular the worry about complexities
introduced by mixing gases. Particular attention was paid to the
problem of carbonization and methods for quantifying it.

It was pointed out that dielectric strength is almost a simple
function of molecular weight. For certain classes of compounds,
dielectric strength increases nearly linearly with molecular weight.
It was also noted that the dielectric strength depends on characteristics
of the molecular bonding, often increasing with bond multiplicity,
e.g., triple bonded molecules tend to have higher dielectric strengths
than the analog double bonded molecules.

In designing a new gaseous dielectric one must realize that vapor
pressure goes down with molecular weight, and toxicity generally goes up
with multiplicity of molecular bonds, trends which are counter to those
just mentioned that give higher dielectric strength.

In this study, they looked at gases that were fluorine containing,
examples of which included: CF_3SF_5, $C_2F_5OC_2F_5$, CF_3OSF_5, $(CF_3)_2S$,
$(CF_3)_3N$, CF_3CF_2CN, $CF_3CF_2CF_2CN$, CF_3SO_2F. As an example, CF_3SF_5 is a
known good dielectric. It has a boiling point of -21 °C and a high
dielectric strength. Unfortunately, it is relatively unstable, and
rapidly decomposes in a low current ($\sim$ 1 ma, 30 sec.) arc into CF_4
and SF_4 with an associated increase in pressure. Only gases with
boiling points below 0 °C were investigated.

The gases selected were screened for dielectric strength in
breakdown tests using a sphere-plane (0.1 inch) gap at pressures of
1, 2, and 3 atm. For gross stability of the gas they looked at both

carbonization at the electrodes and pressure rise in the system after breakdown occurred. Pressure rises of 70% were observed in some cases.

They noted that improvement in dielectric strength over SF_6 depended on gas pressure. The breakdown results shown were consistent with thus far unreported results obtained in tests using sections of CGI line. It was mentioned that one compound was found which looked superior to SF_6 under the tests performed although it was not identified.

Arc stability for different gas mixtures at 2 atm total pressure was determined by arcing the gas for 30, 60, and 90 seconds at low current and then performing analysis for decomposition on recovered samples. The results were reported in terms of percent of gas mixture decomposed. The greatest degree of decomposition was observed for pure fluorocarbons.

No arc induced decomposition of SF_6 could be observed when the gas was analyzed with a gas chromatograph. An example was discussed for an $SF_6+CF_2Cl_2$ mixture where the percent decomposition initially went up with mole percent content of CF_2Cl_2, but a large increase in the decomposition occurred in the region of a 50-50 mixture. Similar results were obtained for other gases. As another example, the decomposition (carbon deposition) in test cells containing $C_2F_6+SF_6$ mixtures was revealed in photographs, and again decomposition depended on mixture ratio. The mixture 90% $C_2F_6+10\%$ SF_6 showed relatively little carbonization compared to 100% C_2F_6. They also looked at mixtures of fluorocarbons with other gases like air, N_2 and N_2O, and found no dramatic improvement over using SF_6. The conclusion of this study was that fluorocarbons are not very

arc stable although arc stability can be improved by adding SF_6.

In summary, the conclusions of this study were: (1) no dramatic improvements relative to SF_6 were found with the new gases studied, with perhaps one possible exception; (2) SF_6 gas blends are possibly useful but the incentive for trying these is at present rather small; (3) the commercially available fluorocarbons are unstable and at this time not considered suitable as a way of achieving gas cost reduction; (4) if fluorocarbons are to be used, then they must be mixed with an arc stabilizer, e.g., SF_6; (5) particle effects on mixtures are unknown and more work on this problem is required. It was also noted that no significant improvement in dielectric strength over $SF_6 + N_2$ or $SF_6 + air$ mixtures could be achieved using SF_6 mixed with available fluorocarbon mixtures.

Questions:

Dr. A. Chutjian of JPL asked if any work was done on arc stabilizers. Other than adding N_2, N_2O, CO_2, and SF_6, little had been done. Dr. Mastroianni expressed the opinion that even a 90% improvement by adding an arc stabilizer was not necessarily satisfactory. Those at Allied Chemical feel that no level of carbonization is tolerable, and unless this condition can be met, the gas should not be considered for use in practical systems. D. E. Massey of GPU Service Corporation pointed out that, from the utility's viewpoint, carbonization in a transmission system, particularly in a transmission line, is not necessarily bothersome since if it results from a flashover, the line will have to be cleaned up or replaced anyway. In a breaker, however, there is concern about effects of carbonization. Again, he emphasized

that we should not be looking at a single gas as a replacement for SF_6, but rather several depending on application, operating conditions, etc.

Bruce Bernstein of EPRI pointed out that there was an apparent inconsistency between the results obtained for carbonization in SF_6-fluorocarbon mixtures reported in this talk and those discussed in the previous talk by Roy Wootton. Particular concern was expressed about the enhanced carbonization in the 50-50 mixture range. R. Wootton of Westinghouse mentioned that black deposits that appear on electrodes after arcing are not always simply carbon. Depending on electrodes used they found very dark deposits that upon analysis revealed little carbon. For example, in the presence of aluminum it is possible to form aluminum fluoride which has a black color.

V. 2:30 p.m. - M. R. Kegelman, E. I. du Pont de Nemours and Company,
Calculation of Vapor Pressure for Dielectric Gas Mixtures

This project was carried out as part of the EPRI supported cooperative effort with the Westinghouse Research and Development Center previously mentioned by Roy Wootton.

It was again emphasized that vapor pressure or volatility is among the more important secondary physical properties of a dielectric gas that must be carefully considered after the primary concern with breakdown strength and arc stability. It was pointed out that vapor pressure effects are sometimes misunderstood by those working in the gaseous dielectrics area. In many respects, this talk served as a kind of tutorial on how to do calculations of vapor pressure for any given mixture of gases or fluids.

One must first consider the different possible binary
mixtures. These are primarily of two kinds: (1) the case where
the liquid phases of the two gases are soluble in each other,
and (2) the case where they are not soluble in each other. The
case where the liquid phases are insoluble is the simplest, for
in this case each component exhibits a vapor pressure independent
of the other. An example of this is the mixture of water and toluene.
The vapor pressures are additive in this particular case, and this
explains why the mixture boils at 85 °C whereas toluene and water
by themselves boil respectively at 110 °C and 100 °C. The composition
of the vapor at a given temperature is independent of the relative
amounts of liquid present in a mixture of immiscible liquids.

It was pointed out that another simple case of a two component
system is the case where one has a so called "permanent" gas such
as N_2 and a condensable gas such as SF_6. Nitrogen can be considered
a permanent gas because its critical temperature is -147 °C, i.e.,
this is the temperature above which N_2 cannot be liquefied at any
pressure. Moreover, liquid SF_6 can dissolve only small amounts of
N_2; therefore, SF_6 in the liquid phase will exert its full vapor
pressure in the presence of N_2.

The greatest misconceptions often creep in for the case where
the liquids in a binary mixture are soluble. In a mixture of miscible
liquids A and B, the molecules of A or B do not experience the same
intermolecular forces that would be present in the pure state, i.e.,
in an environment of their own kind. Therefore, the molecular
restraining forces in a liquid will be different than in pure liquids.

The vapor pressure of the constituents in this case are no longer
additive. Unlike the case of immiscible liquids, the vapor pressure
and gas composition does not depend on the proportions of the liquids
in the mixture. Liquids that are totally miscible generally obey
Raoult's Law which states that "the vapor pressure exerted by a
liquid in solution is proportional to the mole fraction of that
liquid in the solution." Using this law, one can generate plots
such as were shown of vapor pressure versus concentration of some
gas X, for example, in SF_6 at a given temperature say -30 °C. If X
is less volatile than SF_6, one wants to know how much of X can be
tolerated for a given temperature and pressure requirement without
condensation. An example of application of Raoult's Law was considered
for a mixture containing a gas X with a 0 °C vapor pressure of 3.27 atm
in SF_6 which has a 0 °C vapor pressure of 12 atm. Assuming an initial
room temperature loading pressure requirement of 0.44 MPa, one finds
that it is possible to have a mixture containing up to 75% of gas X
without condensation at 0 °C. It was reported that calculations like
this were performed for various SF_6-fluorocarbon gas mixtures. Good
agreement was found when calculated results were compared with
measurements.

They also considered some ternary gas mixtures. The same procedures
used for binary mixtures can be extended and applied to mixtures of
higher component multiplicity.

It was finally noted that Raoult's Law does not apply in all cases,
in particular it will not work for nonideal liquids. In such cases,
one must resort to laboratory measurements.

VI. 3:30 p.m. - L. G. Christophorou, Oak Ridge National Laboratory,

<u>The Oak Ridge Program on Gaseous Dielectrics</u>

The ORNL program was described as comprehensive in that it includes: (1) basic studies of fundamental processes, (2) applied testing, (3) practical measurements, (4) impulse studies, (5) environmental effect studies, and (6) efforts to interface with industry. Highlights from each of these areas were discussed.

Considering first the basic studies it was noted that the main effort here is to understand factors that control free electron energies and number densities in dielectric gases under conditions of electrical stress. There was also concern in this effort to obtain the necessary data on fundamental processes, particularly of gas decomposition, to assess the long term stability and environmental effects of gaseous dielectrics. One should ask the question: what is it that makes a good dielectric? For optimum high dielectric strength, for example, what counts is the ability of the gas to remove the ever present free electrons. A "good" dielectric in this sense will consist of molecules that have both a high electron attachment probability and high electron energy loss cross-sections, so that the mean electron energy can be degraded to reduce the probability for ionization and at the same time enhance attachment so that electrons are readily removed via negative ion formation. The negative ions have a much lower mobility and a much lower probability for inducing ionization by collision than free electrons. In designing a gaseous dielectric to obtain highest dielectric strength, one must, therefore, attempt to <u>maximize</u> the integral

$$\int_0^\infty \sigma_a(\varepsilon) f(\varepsilon, E/P) d\varepsilon$$

and <u>minimize</u> the integral

$$\int_I^\infty \sigma_i(\epsilon)f(\epsilon,E/P)d\epsilon$$

where $\sigma_a(\epsilon)$, $\sigma_i(\epsilon)$, and $f(\epsilon,E/P)$ are the electron attachment cross
section, ionization cross section and electron energy distribution
function respectively, and ϵ, E/P, and I are the electron kinetic
energy, field-to-pressure ratio, and gas ionization potential respectively.
From this, one can understand why detailed microscopic properties,
e.g., attachment rates, collision cross sections, etc., are
useful in preparing a good dielectric.

Ideally, the gases used as dielectrics should be good electron
thermalizers in the sub-excitation energy range. Preferred compounds
should also have high electron attachment cross sections over a wide
electron energy range, say between 0 and 5 eV. It is especially desirable
to have as high an attachment cross section as possible at higher electron
energies. It was pointed out that there is probably no <u>single</u> gas
that has all the desired microscopic properties, and, therefore, the
best dielectrics are likely to be mixtures.

They have discovered in their work that perfluorination of large
hydrocarbons is beneficial in enhancing $\sigma_a(\epsilon)$. Perfluorocarbons typically
have higher (factor of two or more) dielectric strengths than SF_6.
They also have high ionization potentials and relatively high electron
energy loss cross sections. At present, these compounds are viewed as
possible additives to multicomponent dielectric systems. In some cases,
one may need to use only relatively small amounts of these to enhance

dielectric properties. They may not always be suitable as the predominant gas component in power transmission applications because of their relatively low vapor pressures. It was suggested that CHF_3 might be a desirable replacement for N_2 in SF_6-N_2 mixtures.

Concern was expressed that compounds used as gaseous dielectric components to enhance $\sigma_a(\varepsilon)$ should if possible capture the electrons nondissociatively. It was pointed out that decomposition due to dissociative electron attachment ($e \dotplus AB \rightarrow A^- + B$) can occur for some compounds even for electrons with near zero energy. It was reported, for example, in the recent mass spectrometric work of I. Sauers, et al. (J. Chem. Phys. $\underline{71}$, 3016 (1979)) that for $1,3$-C_4F_6 the yield of dissociative attachment products far exceeds the yield of the parent molecular negative ions in the relevant electron energy range from 0 - 9 eV expected for the electron energy distribution, $f(\varepsilon, E/P)$, under typical practical operating conditions. On the other hand, the compounds c-C_4F_6, 2-C_4F_6, and c-C_4F_8 were not found to easily decompose by dissociative attachment at these electron energies.

They have looked into the question of electron detachment, i.e., how effectively the electron is bound to a negative ion. Various detachment mechanisms were examined such as electron collisional detachment, photodetachment and field induced detachment. They concluded that the most important electron detachment mechanism is collisional detachment, either associative or nonassociative. By theoretical calculation, Professor Harold C. Schweinler who has worked with them finds that detachment is not likely to be important under practical conditions. Fields on the order of 10-20 MV/cm are, for example, required to detach, with significant probability, negative ions with electron affinities of 1 to 1.5 eV.

Experiments in this program have shown the trend that increasing electron scattering cross sections increases breakdown strength in a gas. In this process, the formation of temporary negative ion resonances (quasi-trapping of electrons by a molecule) is important since this mechanism enhances the collision cross section. Nitrogen is a relatively good electron thermalizer because it has resonance-enhanced inelastic electron scattering at low electron energies (around 2.0 eV). Also, molecules with multiple bonds, high electric dipole moments, and high static polarizabilities tend to have high electron scattering cross sections.

It was argued that ionization cross sections are relatively unimportant compared to attachment and inelastic electron scattering cross sections. One generally cannot improve dielectric strength of the gas much by reducing the net ionization cross section. If the system is effective at thermalizing and otherwise removing electrons with sufficient energy to cause ionization, then ionization is not of significance.

They have studied mixtures of perfluorocarbons with nitrogen and found that most of these mixtures have higher dielectric strengths than SF_6 particularly in nonuniform fields. Randy James at ORNL observed synergistic behavior in uniform field breakdown strengths for the mixtures $1-C_3F_6+SF_6$ and $1-C_3F_6+c-C_4F_8$, i.e., the breakdown strength for some mixture ratios exceeds that for either component alone.

A study was carried out with various binary mixtures with one electron attaching and one dipolar gas component as a thermalizer. In these cases, synergisms were observed. However, for non-dipolar

plus attaching gas mixtures no synergisms were found. It was thus argued that observed synergistic effects were due to enhanced electron thermalization in dipolar gases resulting from higher scattering cross sections.

In discussing the practical studies it was mentioned that they have looked at (1) breakdown in different electrode geometries, (2) surface roughness effects, (3) contaminant effects in the gas, (4) impulse breakdown, (5) corona onset, (6) nonuniform field effects, and (7) effects of temperature. They are also planning to investigate accelerated life tests.

Some of the preliminary conclusions from these practical studies are:

(1) All perfluorocarbon gases and mixtures which are superior to SF_6 in uniform field measurements continue to be as superior under practical conditions. It was stressed that the perfluorocarbon-N_2 mixture under cylindrical electrode testing suffers less than comparable SF_6-N_2 mixtures. The synergistic effects in SF_6-N_2 become less as field becomes more nonuniform, whereas this is not the case for similar perfluorocarbon-N_2 mixtures. As the field becomes more nonuniform, the percentage of perfluorocarbon needed to achieve a given dielectric strength becomes increasingly less than the corresponding amount of SF_6 needed to achieve the same conditions.

(2) Perfluorocarbon-N_2 mixtures perform satisfactorily as surface roughness increases as compared, for example, to SF_6-N_2 mixtures.

(3) The breakdown strengths for SF_6 and SF_6-N_2 mixtures were found to be independent of temperature.

(4) The C_4F_8-SF_6 mixture was found to have much higher negative
polarity impulse breakdown voltage in a point-plane configuration than
pure SF_6.

They have looked at gas decomposition due to initial electron
collisions (previously mentioned dissociative attachment) and decomposition
under stress and breakdown. The breakdown products have been identified
using a gas chromatograph-mass spectrometer with selective mass-to-charge
ratio positive ion monitoring. One observes many decomposition products
under conditions of continuous sparking and many of these are perfluoro-
carbons, contrary to what many have been led to believe. They found that
CF_4 production in sparking actually went down as the perfluorocarbon
content in perfluorocarbon-SF_6 mixtures went up, indicating that the source
of CF_4 is really derived from reactions involving products from SF_6.
It was argued that there may be mixtures that optimally inhibit the
production of certain gaseous decomposition products. The monitoring
of CF_4 was in fact proposed as a quantitative method for testing
optimization of mixtures to minimize undesirable decomposition. It was
noted that the addition of N_2 to perfluorocarbons decreases formation
of CF_4.

It was suggested that the following mixtures deserve further study:
c-C_4F_8+SF_6, c-C_4F_8+SF_6+N_2, c-C_4F_8+SF_6+CHF_3, and c-C_4F_8+SF_6+1,1,1-$C_2H_3F_3$.
These mixtures, for example, do not appear to have serious carbonization
problems.

Questions:

R. J. Van Brunt of NBS questioned the importance placed on using
dissociative electron attachment as an indicator of gas stability since it is

known, for example, that this occurs in SF_6 even at very low electron
energies, yet the decomposition products seem to recombine after a time
to reconstitute the gas. Perhaps the subsequent chemical reactions
that occur after dissociative attachment are more important.

It was pointed out by Dr. Christophorou that in the case of SF_6
the F^- production is predominantly at higher electron energies (greater
than 2 eV) and thus may not be important in a practical system where
the number of "high energy" electrons above 2 eV would be very small.

Ara Chutjian of JPL noted, however, that dissociative attachment
in SF_6 leading to formation of SF_5^- can occur even down to threshold.

In his reply, Dr. Christophorou recalled that the cross section
for SF_5^- production is roughly two orders of magnitude smaller than
that for SF_6^- formation for electron energies below 0.1 eV.

There was a question by Dr. J. Dutton, University College Swansea,
about the downgrading of the importance of ionization. He pointed out
that although this may be true under static breakdown conditions where
the electron energy distribution is thermalized, it may not be true for
impulse conditions where the electron energy distribution can be quickly
brought up to a high mean energy value.

It was admitted that under highly inhomogeneous field conditions
ionization may indeed be an important consideration.

VII. 4:00 p.m. - J. Castonquay, Hydro-Quebec Institute of Research,
            Analysis of Trace Decomposition Products in Gaseous
            Dielectrics

In the research described in this talk, they have taken the
practical point of view of developing analytical techniques to observe

gaseous decomposition in real power systems. It is known that under electric discharge conditions SF_6 can decompose readily in the presence of impurities and this is a problem that needs to be addressed in the development of new gaseous dielectrics that might be considered as replacements for SF_6.

In their work, they have performed analysis of gases in practical high voltage systems designed to operate with a flashover voltage of 1 MV with 3 atm SF_6 which had undergone breakdown tests. In this analysis, they were able to identify certain decomposition products such as SO_2 up to the 125 ppm level.

Laboratory decomposition studies were performed in a teflon cell equipped with a steel needle electrode and aluminum cathode. Recent investigations of decomposition in such a cell caused by discharges and partial discharges included the following artificially "contaminated" mixtures: pure SF_6, SF_6+10% air, SF_6+9% CO_2, and SF_6+10% CO. It was discovered that the decomposition for all of these mixtures was roughly at the same rate. From this, one might conclude that the presence of most atmospheric constituents in SF_6 does not appreciably accelerate the rate of decomposition over that in "pure" SF_6.

To determine the extent of decomposition, they looked for the following contaminants: SOF_2, SO_2F_2, SOF_4, F_2CO, and CH_4. It was noted that oxygen as well as CO were consumed in reactions leading to many of these products. Also they found that white crystals were deposited at the bottom of the cell which hydrolyzed in air, and thus were assumed to be aluminum fluoride. Moreover, with the aid of x-ray fluorescence they found that after the tests aluminum was deposited throughout the cell.

They also looked at the following mixtures: SF_6+11% CH_4 and SF_6+9.3% C_2H_2, and found that the decomposition was faster than in pure SF_6. In these cases, SOF_2 was one of the most prevalent decomposition products. These results indicate that hydrocarbons apparently induce a more rapid decomposition of SF_6 than even H_2O, which has always been considered one of the most harmful forms of gas contamination. It was noted that C_2H_4 in SF_6 gave the highest observed rate of decomposition in a high-voltage, low-power arc.

It was emphasized that the fluorine atom is the main primary decomposition product in SF_6, and this atom reacts readily with whatever it encounters in a system. It would thus appear that hydrocarbons are readily attacked by free fluorine.

In their work, analysis of the gases was done by syringe injection into a chromatograph. With 200 microliters of contaminated SF_6, they can now measure concentrations of contaminants down to the ppm level. There are, of course, some contaminants that are difficult to observe. In particular, it was pointed out that HF and SF_4 will attack oxides and are difficult to analyze. For SF_6, it was argued that SOF_2, SOF_4, and SO_2F_2 are the main decomposition products that should be monitored at the ppm level in order to determine quality of the gas. The most powerful recommended analytical technique is the combined gas chromatograph-mass spectrometer.

In these studies, they used what might appear to be unusually high gas impurity concentrations. This was done, however, to simulate what might happen, for example, during flashover near an epoxy spacer where contaminant levels due to release of gases from solids might be considerably higher than in the gas under ordinary conditions.

In their analytical technique, they used a chromatograph with a column constructed of Teflon tubing and Porapak-Q support material. A quadrapole mass spectrometer was used as a detector. To enhance chromatographic sensitivity, very short columns were used since short columns require less clean up. This was done, of course, at the sacrifice of separation in column elution times for the various decomposition products of interest. It was pointed out that if one is to observe SF_4, one must repeatedly inject the same mixture into the column for up to one hour in order to precondition it before attempting an analysis for this gas component. The SF_4 will react with SiO_2 or H_2O in the column and convert to SOF_2. In chromatographic analysis of fluorine compounds, one of the problems is the presence of gaseous silicon compounds particularly SiF_4 which can result from such reactions as

$$2SF_4 + SiO_2 \rightarrow SiF_4 + 2SOF_2$$

and

$$4HF + SiO_2 \rightarrow SiF_4 + 2H_2O \ .$$
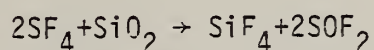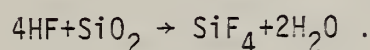
For this analytical work, a silicon rubber membrane separator was used at the gas chromatograph-mass spectrometer interface. Helium was the carrier gas used in the column.

Various loss mechanisms in the gas chromatograph-mass spectrometer system which limit sensitivity were discussed. These include: (1) losses within the column due to gas transformations or conversions, which increase with column length, (2) losses in the membrane separator, particularly

if the gas of interest has low solubility in the membrane such as is the case for SF_6 in a silicon rubber membrane, (3) losses in the mass spectrometer as results, for example, from the finite ionization efficiency (typically only about 1%) and the finite ion detection efficiency. Despite these losses, analytical sensitivity down to a few ppm should be possible with a gas chromatograph-mass spectrometer system. Because the ionization chamber was operated at 180 °C, some SF_6 was slightly decomposed on the chamber walls giving rise to artificial ion peaks in the mass spectra which are more characteristic of SOF_2.

Results from the gas chromatograph-mass spectrometer were compared with other "standard" methods of analyzing SF_6 such as ASTM 2284. It was found that the recommended procedures do not always give the sensitivity for SOF_2 that is claimed and should perhaps be reexamined.

Questions:

Dr. Ed Walsh of Westinghouse asked about the toxicity of SOF_2 and SO_2F_2. It was noted in reply that one can breathe these at the 1 ppm level for ten hours per day, five days per week without ill effects.

Dr. Christophorou of ORNL commented that in mixtures of SF_6 with fluorocarbons and/or with N_2 some of the byproducts of SF_6 decomposition are picked up by the fluorocarbons.

Dr. Devins of GE asked if S_2F_{10} was observed. It was stated that they did not try to find it, and, moreover, its presence at small concentrations might be difficult to observe. If you can detect SOF_2 you will certainly not detect S_2F_{10}.

Dr. R. J. Van Brunt of NBS asked if they had tried to use a jet separator at the gas chromatograph-mass spectrometer interface. They have

not tried a jet separator yet but have plans to do so. The comment was
added that the performance of a jet separator is very sensitive to
carrier gas flow rate in the chromatograph.

VIII. 4:30 p.m. - R. J. Van Brunt, National Bureau of Standards,

        Study of Corona Characteristics and Corona Chemistry

        in Gaseous Dielectrics

        In this talk, a description was given of a DOE-sponsored
research program at NBS that is concerned in part with gaseous
dielectrics. The main focus of this work is on providing funda-
mental information and data useful in the development of more
meaningful tests and models of gaseous dielectric performance.
Particular emphasis at the present time is on the problem of long term
effects, such as chemical changes that result from subjecting a gas to
continuous high stress conditions. The four primary objectives of the
program include: (1) partial discharge (corona) characterization,
(2) chemical diagnostics development, (3) swarm and breakdown data
evaluation, and (4) fundamental mechanism identification.

        Considering the first objective, it was noted that partial discharges
(corona) occur in practical systems around particles, sharp protrusions,
at interfaces, etc., and may be difficult to avoid or detect. It
represents a power loss and can in some cases be a major cause of
insulation deterioration. Very little fundamental work has been done
on corona in SF_6 and other electronegative gases or gas mixtures that have
possible usefulness as gaseous dielectrics. Thus far in this program,
they have looked at the problem of measuring and defining corona inception
for ac and dc voltages which has included performance of measurements to

electrically and optically characterize the phenomenon. Corona in SF_6 appears primarily in the form of pulses for both positive and negative polarity. Attempts are now underway in their laboratory to characterize the corona pulse frequency and pulse height distributions as a function of operating conditions as defined, for example, by gas pressure, applied voltage and electrode configuration. They have also looked at the pulsed optical emission from corona in SF_6 and SF_6+N_2 mixtures in an attempt to determine optical spectra, intensity distributions, and correlation with simultaneously observed electrical pulses.

The second objective indicated above involves development of chemical diagnostic techniques which can help provide information about corona induced chemical changes in the gas that might be correlated with observed changes in corona characteristics. The primary technique under development now is a gas chromatograph-mass spectrometer system for in situ analysis, which is similar to that described in the previous talk. It was noted, however, that this technique has its limitations in that it only indicates the initial and final conditions of the gas, i.e., the relative amount of decomposition that has occurred in the gas after it has been subjected to corona or discharges over a given period of time. It tells very little about the intermediate chemistry that occurs during corona. Other techniques are under development to learn more about fundamental processes that occur in discharges and these include: laser induced opto-galvanic spectroscopy, and optical emission and absorption spectroscopy.

At the present time, the third item in the list of objectives is concerned entirely with evaluation of swarm data for electronegative gases.

This work is being conducted at the Atomic Collisions Data Center,
Joint Institute for Laboratory Astrophysics, University of Colorado
and National Bureau of Standards, Boulder, Colorado 80309.
Professor Jack Dutton from the University College of Swansea is providing
assistance in this effort. Consideration is being given to extension
of this project to include fundamental data on electrical breakdown
and sparking potentials.

There are also plans to do experiments on fundamental mechanism
identification. The purpose here is to identify collision
processes and determine their relative importance in high pressure gas
discharges. Processes of interest include, for example, collision-induced
metastable quenching, field-enhanced collisional detachment, dissociation
rates, etc.

The remainder of the talk dealt with recent results obtained on
characterization of corona phenomena in SF_6 and SF_6+N_2 mixtures. The
measurements were performed using a stainless steel point-plane electrode
configuration. Results were reported on measurement of dependence of
corona pulse rate on applied voltage and current. Pulse detection and
counting techniques were used to determine onset of corona under ac and
dc conditions. For ac conditions, corona observations were restricted
to selected phase intervals so that separate measurements of positive
and negative onset within each half cycle could be made. The negative
corona onset in SF_6 under both ac and dc conditions always occurs at the
lower voltage. It was observed that the negative corona onset voltage
was the same for both ac and dc under all conditions. The positive
corona onset voltage, however, was in general different for ac and dc, and

this difference increased with increasing gas pressure. This would appear to be due to the fact that as pressure increases the ionization on one half cycle begins to have more influence on development of corona on the next half cycle. This was suggested also by the frequency characteristics of negative corona which, at higher pressures, display abrupt discontinuities at voltages corresponding to the positive corona onset. The results of these measurements indicate that measurement of dc positive corona onset is not necessarily a good indicator of what would happen under ac conditions.

It was noted that the pulse shape characteristics are quite different for positive and negative corona in SF_6 and $SF_6 + N_2$ mixtures. Plots of the pulse height distributions for positive and negative corona for various operating voltages and gas pressures were shown. It was pointed out that over the pressure range of 50 to 500 kPa the mean amplitude of the negative corona pulses is typically an order of magnitude lower than the mean amplitude of the positive corona pulses. The repetition rate of negative corona pulses, however, is considerably higher, which explains why the average corona current can be roughly the same for both polarities. Positive corona starts as low level avalanches which eventually develop into a pulse burst activity preceded by a "large" streamer pulse. The average length and intensity of the bursts tends to increase with decreasing gas pressure and increasing voltage. The burst activity manifests itself as structure in the pulse height distribution, and this structure seems to depend on gas composition, being quite different, for example, in $SF_6 - N_2$ mixtures compared to pure SF_6.

Negative corona, particularly at lower pressures (< 300 kPa), starts as single relatively large pulses ($\sim$ 10 pC) and then quickly

changes to a quasi-glow condition consisting of many closely spaced pulses as the voltage is increased. Trichel pulses such as occur in N_2 contaminated with electronegative gas were not observed in SF_6 in the pressure range 50 to 500 kPa. This type of activity was also not observed in the SF_6+N_2 mixtures studied.

There appears to be some indication that pulse height distributions are sensitive to small changes in gas composition resulting from contamination or electrical discharges.

Questions:

Dr. A. H. Qureshi of the University of Windsor pointed out that the results described in this presentation appear to be quite consistent with recent results obtained at the University of Windsor. He noted that their observations of optical pulses correlated well with electrical observations of corona pulses.

Dr. Van Brunt noted that although they also obtained good one-to-one correlation in recent measurements, there were systematic differences in pulse shape between the optical and electrical signals, possibly due to variations of the emission spectra with time.

Dr. Ken Davies of Westinghouse asked if observed pulse frequency correlates with ion transit times. The answer was that this has not been looked at. This question is difficult to answer for the conditions under which the measurements are made where space charge distortion of the field might be significant.

September 11, 1979 - B. S. Bernstein, Chairman

IX.   9:00 a.m. - C. M. Cooke, Massachusetts Institute of Technology,
Basic Factors Influencing Reliability

This talk was concerned with variations and causes for variations
of breakdown voltage in gas insulated apparatus. One question of
relevance with regard to reliability is the expected breakdown voltage
for a single or small number of applied pulses without regard to pulse
shape or pulse length. This can then be extended to ask what happens
after many years of operation? In this case, one wants to know, what
are the rare breakdown voltages after many pulses have occurred?
The question of concern is what is the probability that a given pulse
will cause breakdown?

This further leads to the question of how to test for acceptable
performance and how one system should be compared with another in the
cases where the systems differ, e.g., relate the performance of one
particular kind of gas with that of another. In beginning the discussion,
the following assumptions were introduced: (1) the system is operated
in a partial discharge free mode which implies no decomposition in the
gas medium, (2) the electric field is relatively uniform and thus space
charge distortions are neglected. Allowance will, however, be made
for surface roughness which can cause localized nonuniform fields. The
problem then is to find a way of predicting the performance of a gas
insulated system. It was pointed out that at high gas densities electrode
effects on breakdown begin to become important.

The breakdown under the conditions specified here is not a glow
discharge but rather a sudden hot spark. In their work, they had

assembled data on breakdown versus time. A kind of universal
breakdown curve was shown that indicated how the withstand voltage
increases dramatically as the time duration of applied voltage is reduced.
The well known fact was again emphasized that for practical sized systems
operated at SF_6 gas pressures considerably above 1 atm the breakdown
voltage after long times is considerably below the ideal theoretical
limit of (89 kV/cm-bar). However, at 1 atm the long time results
come close to the theoretical limit.

The data from which the universal breakdown curve was derived were
for natural irradiation, i.e., there were no external sources of electrons
such as result, for example, from deliberate irradiation with UV, x-rays,
or gamma rays. The question was then raised concerning the origin of the
universal curve shown, i.e., how does one explain the observed time delays
for breakdown?

The problem was broken up into three parts, i.e., three origins of
delay were separately considered. These are: (1) the time required in
waiting for an initiation event such as a free electron in the appropriate
place, a particulate or a plasma, e.g., a surface oxide layer breakdown
which causes a pulse of charged particles; (2) consideration of false
starts which would correspond to the situation where an initiating event
occurs but then fizzles out and does not develop into breakdown; and
(3) the time delay associated with the formation of a conducting channel.
Each of these were next examined in some detail.

Item (3), the formation time, was considered first. This is the
time necessary for the voltage to collapse after the initiating electron
appears. If a slight overvoltage is applied this is usually a very short

time, less than a nanosecond. One can argue then that the formation time is not significant in many situations.

Next the question of false starts was looked at. This was done by considering the electron avalanche as being a link that takes the gas from its insulating state to its conducting state. Either the Townsend or Streamer criterion can be considered in which a large avalanche growth is what is required to initiate breakdown. The question was posed: given n starting electrons some place, what is the probability that there will be a sufficiently large number of electrons produced, say 10^8, required by the criterion considered? The function $P(n,x)$ was defined as the probability of having n electrons after the avalanche develops to a distance x. A sum was then performed over all n greater than some critical value n_c determined by the chosen criteria.

$$P = \sum_{n \geq n_c} P(n,x) \ .$$

The result is not sensitive to the choice of n_c. This avalanching probability function has been evaluated for SF_6 gas assuming a sharp protrusion on a surface. Plots were shown of relative applied voltage to the gap versus the probability of growth to breakdown P for $n_c = 10^8$ and a given number of initiating electrons. The probability function is computed by asking the question that as an electron (or group of electrons) is moving through the gas under a defined set of applied field and pressure conditions, so that there are well defined average ionization, attachment coefficients, etc., what is the probability that

in the next increment of time the avalanche will either have grown or decayed? This is answered by solving a probability differential equation that describes the probability of increase in size per unit of travel.

The novel feature of this analysis is that a nonuniform field has been introduced. (The uniform field breakdown case has previously been solved). The probability curve generated is useful in test evaluation. One makes a test for a given period of time at some voltage and then backs off on voltage and waits. One then asks the question, how long must one wait on the average for breakdown to occur under the new conditions? Based on purely the statistics of avalanche growth considering false starts only, i.e., avalanches that do not achieve $n_c = 10^8$, one can make a prediction. The problem of false starts is thus handled by merely considering avalanche growth statistics.

Finally, other ways that one can get a time delay in breakdown were considered, i.e., those included in category (1) of waiting for an initiating event. One assumes a voltage pulse applied to a gap. Two things can then happen. First of all in a gap to which no voltage is applied there will be a certain number of initiating electrons produced by cosmic radiation and background radiation. One can predict the distribution of these. As soon as a voltage is applied, these charge carriers will be swept out of the gap. Thus, as voltage is raised higher and higher there will be a time at which there are no more carriers in the gap. It was noted, however, that the clearing time depends on mobility of the electrons and rate of voltage increase. It is evident then that even though the applied voltage exceeds the breakdown voltage, breakdown

will not occur due to the absence of initiating electrons. The concern

thus shifts to the mechanism by which more charge carriers are introduced

once the high voltage level is reached. Given a carrier, it can be assumed

that breakdown will occur. The question to be asked then is, once the

gap is cleared and voltage exceeds breakdown how long does it take before

a new initiating electron appears? This can apparently take considerable

time. Without initiating electrons one can apply five or perhaps even

ten times over-voltage without occurrence of actual breakdown. Of course,

at sufficiently high fields initiating electrons can come from field

emission, although it was mentioned that contributions from field emission

may be difficult to determine. Their work seemed to show less effect from

field emission at a given field than might be expected, particularly

from experiments performed in vacuum.

At this point, the discussion turned to the effect of protrusions.

Around some of the higher protrusions there is a volume in which avalanche

growth can take place despite the fact that this may not be possible in

the ambient applied field E_0, or around smaller protrusions. It was

pointed out that the active volume around n protrusions should be

roughly proportional to

$$\sum_i k_i (E_0) E_0^3 .$$

This is because the equipotential surfaces are nearly spherical around

any protrusion. The total active volume in a gap can grow very rapidly

with applied electric field. For breakdown to occur, the initiating

electron must appear in the active volume. According to this model, the

probability that an effective initiating electron will actually appear obviously increases with E_o, surface roughness, and duration of overvoltage, i.e., length of voltage pulse.

It should be possible using the voltage-time-to-breakdown curve to predict breakdown after n units of time from data on one unit of time. It was pointed out in closing that the whole picture is not merely waiting time for electrons. There are other sources of breakdown initiation such as from particles and along solid dielectric insulators, the internal charging of which can sometimes introduce sufficient field distortion to enhance breakdown.

Questions:

Dr. J. Devins of GE brought up the question of attachment as a mechanism for removing initiating electrons and effectively diminishing the life time of a free electron. It was stated in reply that inherent in the calculation is the tacit assumption that the number of carriers at the initial time is in a steady state which would necessarily include attachment rates.

Dr. L. Christophorou of ORNL asked about the mobilities used in the calculation. In answer, it was noted that the mobilities used were those for electrons in typical fields.

The question was raised concerning effect of system size, e.g., area effects. Dr. Cooke pointed out that the model results do indicate size effects.

X. 9:30 a.m. - J. Dutton, University College of Swansea,

Swarm and Breakdown Data for Gaseous Dielectrics

The purpose of this talk was to show in a general way how data obtained from the study of electron swarms and breakdown are related to answering some of the central questions which arise naturally in considering improved gaseous insulation. For any practical system, the three main questions that come up concerning electrical breakdown are: (1) what is the V_s (lowest voltage at which breakdown will occur), (2) what is the space and time dependence of current growth $I(x,t)$ when $V > V_s$, (3) and how do V_s and $I(x,t)$ change with time and as a result of current flow.

To begin to answer these questions, the first thing that one must do is define the system. One needs to know (1) the electrode geometry, (2) the free electron availability, (3) the type of voltage applied, i.e., ac, dc or impulse, (4) the physical properties of the system namely the type of gas and electrode materials as well as the state of those electrodes. One can then either directly measure the quantities of interest, namely V_s and $I(x,t)$ or use a physically based model. These two procedures are, of course, complementary. One wants to know under what conditions one can with some confidence use physically based models and under what conditions one still needs to rely on direct measurements.

It is first necessary to consider the input requirements for a modeling effort. These are: (1) initial electric field distribution $E(x,t)$ since all processes depend on electric field, (2) processes going on at the electrodes, although in many cases rather inexact knowledge of that is adequate for modeling, (3) gas number density N, and (4) either the

cross sections for gas collision processes as a function of energy, or alternatively the swarm coefficients, i.e., the drift velocities, diffusion coefficients, excitation, ionization, attachment and detachment coefficients, etc., as a function of E/N, and N.

If cross sections are to be used, then one must first set up an energy balance from which one can get an electron energy distribution. The cross sections are integrated over that energy distribution and inserted into the charge conservation equations to obtain the sparking potential V_s and $I(x,t)$. The use of swarm coefficients can be somewhat easier since in the determination of swarm coefficients the integration of the cross sections over the electron energy distributions has already been performed. The charge conservation equations must then be solved with appropriate boundary conditions.

The questions to be asked are: what can we predict from the model and how much confidence can we have in the results? It was noted that we can calculate sparking potentials at low fields and this has been done for quite some time. We can also simulate $I(x,t)$ and this has, for example, been done for current growth in nitrogen discharges in the low pressure region.

In considering the question of confidence in modeling it was mentioned that our present capability is limited. We can make reasonable predictions for uniform fields for V_s and $I(x,t)$ up to at least 600 kV provided $E < 10^7$ V/m. For nonuniform fields we can determine dc corona onset voltages and model early stages of current growth $I(x,t)$ provided the field is of sphere-plane configuration and is not too convergent. The limitation here is determined by the combination of computing power and computer methods.

For the near future, within the next few years, it would appear possible to extend modeling further into the more convergent nonuniform field regions and predict later stages of I(x,t) and eventually, therefore, the actual breakdown voltage V_s. For the distant future, there is hope of extending the modeling to the region where fields at the cathode exceed 10^7 V/m such as occurs in the high pressure situation discussed in the previous talk. At present, it appears unlikely that modeling could be attempted in cases where there is an ill defined initial field.

It was noted that the above discussion applies to single gases. The case for gas mixtures was considered next. The question here is: what are the prospects for modeling breakdown in mixtures? It was emphasized that a mixture is in general not simply the sum of its constituent parts. Examples of special problems that appear for mixtures were discussed.

The first mixture considered was that of N_2O+O_2. In this mixture O_2 is weaker, having a dielectric strength only about three fifths that of N_2O. However, adding a small quantity of O_2 actually increases the breakdown strength of N_2O. This is another example of the synergistic effect noted in previous talks. Synergisms have also been observed in mixtures of N_2 and freons. The ionization coefficients in these mixtures were found to exhibit a very peculiar dependence on relative gas composition.

In mixtures there can be marked changes of the electron energy distributions as compared to those expected from pure gases. Also, collision processes can be introduced which are not possible in single gases. For example, in the N_2O+O_2 mixture it is believed that the reaction

$NO^-+O_2 \rightarrow NO+O_2^-$ is introduced which effectively competes with the electron detaching reaction $NO^-+N_2O \rightarrow N_2O+NO+e$. This mechanism may explain the enhancement of N_2O dielectric strength by addition of the weaker dielectric O_2. For mixtures one cannot reliably use swarm coefficients to do the modeling. Except as a first approximation, one must resort in this case to use of basic collision cross sections.

Although modeling for gas mixtures is indeed more complex than modeling for pure gases, there is good evidence that modeling for mixtures can nevertheless yield reliable results. Examples were cited of recent successes in modeling of gas mixtures used in laser discharges and in prediction of breakdown in SF_6+He mixtures.

It was concluded that ready access to critically evaluated collections of swarm coefficients and collision cross section data were essential to a successful modeling effort. Mention was made of the existing program to compile and evaluate swarm data at the JILA-NBS Atomic Collisions Data Center. In closing, the question was put forth to the meeting concerning the need for an organized program for collection and critical evaluation of breakdown and sparking potentials. Would a handbook giving this kind of information be useful?

Questions:

Dr. D. Miller of Gould-Brown Boveri brought up the question of the importance of photoelectric processes at the cathode and thus the importance of cathode materials. Dr. Dutton replied that at low fields the effect of the cathode is indeed included in the boundary conditions. In the high field region the surface becomes dominant. The question in this region is: what is the feature of the cathode that is dominant,

e.g., is it surface roughness, surface deposits, geometry, etc.? This was discussed in the previous talk by Dr. Cooke.

Dr. Cooke of MIT noted that swarm parameters are an average quantity and wondered how long it takes an electron at rest suddenly appearing in the gap to achieve the "average" conditions. In reply, it was said that this depends on the number of collisions with gas molecules, but should happen very quickly.

Dr. L. Christophorou of ORNL mentioned that relaxation times for electrons are typically on the order of $\sim 10^{-7}$ sec./Torr. He also again emphasized that in mixtures it is not sufficient to merely weight relevant parameters according to the partial pressures of the components.

Panel Discussion

B. Bernstein, Chairman

Bruce Bernstein (EPRI):

In his opening remarks, Mr. Bernstein expressed concern about the needs for future research. He pointed out that there are academic, industrial and utility needs and perspectives that should be examined. He then discussed highlights of the previous talks. The panel was reminded of Dave Massey's point that if substation size can be reduced, cost is not an extremely important factor. In their talks, Roy Wootton and Martin Mastroianni offered the opinion that it was an unlikely possibility that a single gas could be found that would be superior to SF_6 in all respects. Various promising mixtures, however, were mentioned by Loucas Christophorou and Roy Wootton. Martin Mastroianni expressed concern about degradation in mixtures containing about 50% fluorocarbons.

Carbonization was discussed and the question was raised about how important this problem really is in an actual power transmission line since clean up would be necessary following flashover independent of the degree of carbon deposition. Mat Kegelman described a method for calculating the maximum amount of additive dielectric gas that could, for example, be put in SF_6 and still meet the necessary vapor pressure requirements. Concerning basic, fundamental studies, the questions there are how do we fit in, utilize and justify measurements for example of ionization coefficients, attachment processes, etc., from the point of view of aiding development of the utility's needs for future power systems? How do the measurements of R. Van Brunt at NBS and others on fundamentals of partial discharges fit into the picture? The question of toxicity was raised by Ed Walsh but not addressed in depth in any of the formal talks.

Dave Massey (GPU Service Corp.):

He noted that $900,000 might be paid for a 500 kV breaker that is tripped only once in five years. The utility people would like to know if there is any way that this can be done at lower cost. A better gas might be part of the answer. Again it was emphasized that the tripping rate for breakers is roughly only one per 100 miles per year. Thus, one is paying a high price for protective equipment that remains idle for long periods of time. Concerning carbonization, this may not be a big problem in a transmission line, since clean up is always required after a failure. One should be concerned though that the clean up operation can be performed thoroughly and safely. The concern with environmental acceptability of gaseous decomposition byproducts may be too great at this point. The power industry is after all used to handling toxic and

hazardous materials, and problems in transmission systems are not likely to be comparable to those, for example, in nuclear power plant operation.

Bruce Bernstein (EPRI):

He asked if substation size reduction should take priority.

Dave Massey (GPU Service Corp.):

He replied that it should, and added the comment that the present SF$_6$ insulated substation is a plumber's nightmare.

Jacques Castonguay (IREQ):

He mentioned that Hydro-Quebec has up to now installed one metal clad SF$_6$ substation. He also pointed out that one should be careful to distinguish between insulation used in static systems compared to that used in dynamic systems. In a static system, even if decomposition occurs, the products which result are quite likely to be good dielectrics and the system may continue to operate for many years. The byproducts of SF$_6$, for example, are generally good dielectrics since they tend to be highly electronegative. Therefore, from the simple dielectric strength point of view, the effect of gas decomposition may not be extremely important. He noted also that a 50% SF$_6$÷N$_2$ mixture is nearly as good a dielectric as pure SF$_6$. Specialized mixtures could be used for breakers. If these same mixtures could also be put into a metal clad cable that would be desirable, but the mixture criteria for these two applications may be quite different. Again we must ask, what are these criteria? Is it immunity to particles, impurities and surface defects for example? He pointed out that SF$_6$ is not particularly ideal in being able to meet these criteria. Also SF$_6$ has a peculiar, unpredictable

behavior in terms of its pressure effect.

Michael Pohl (Air Products):

He noted that they used the standard ASTM test to determine contamination levels in the SF_6 gas which they manufacture, and he was disturbed about findings reported by J. Castonquay at this meeting concerning sensitivity of this test. However, they do not view it as an absolute test, i.e., they cannot detect exactly how much hydrolyzable fluoride is present. All they say from the test is that the concentration is below a particular level. He also pointed out that Air Products provides a service of performing analysis for users of gas that has been in a breaker. This requires extraction of a gas into a cylinder which is then shipped to the testing laboratory.

Jacques Castonquay (IREQ):

Those at the Hydro-Quebec Laboratory have taken the view that it might be preferable to develop techniques to analyze gases on site (in the field) since it is quite likely that fluoride content will be perturbed and change during the time of sampling and shipping.

Michael Pohl (Air Products):

At Air Products, they have been investigating these changes in fluoride content due to sampling by using samples of gas with controlled levels of fluoride contamination. They have indeed observed large changes in fluoride content after the sample has been held in the cylinder for some time. The decomposition product concentrations observed immediately after arcing may be quite different from those observed a day or so after arcing.

Loucas Christophorou (ORNL):

He also noted that Dr. I. Sauers in their laboratory has observed that fractional content of certain decomposition products changes with time after arcing. He brought up again the question of costs discussed by Dave Massey.

Dave Massey (GPU Service Corp.):

He reminded everyone that it was the total cost that was significant and increase in gas costs could certainly be tolerated if these were accompanied by compensating factors such as size reduction or increase in efficiency. He noted that the cost of losses in a transformer are greater than the cost of a transformer.

Bob Noberini (Consolidated Edison Company):

The utilities have a big interest in 345 kV transformers that are cooled by SF_6 and/or other gases having desirable insulating properties. He mentioned that the Consolidated Edison Company is acting as a host utility for DOE on testing of such transformers in the single phase 200-400 MVA range. Right now there are problems in dealing with oil cooled transformers of this power level. Considerable time, for example, is required in the installation of such equipment. With gas insulated systems, it is hoped that the equipment can be manufactured, sealed and tested at the factory and be ready for immediate installation in the field. Other desirable aspects of gas insulated systems in transformers would include the fact that they are non-flammable, non-explosive, relatively non-polluting, have a lower noise level than oil systems and a lighter shipping weight. He pointed out that they now have an SF_6 insulated substation on the west side

of Manhattan with five transformer banks and a capacity for another
five. All the transformers, however, are oil cooled, and it is their
hope to eventually replace these with gas cooled equipment. They
could, he noted, reduce the size of this substation considerably
by going to gas cooled transformers because the transformer is the
single largest piece of equipment. One of the hopes from future use
of SF_6 or other gas insulated equipment is that it will help solve the
current and impending corridor crisis. They simply cannot pack any
more power into existing right-of-way by present methods.
Consolidated Edison has a "now" problem in terms of high load density,
very tight corridor, and zero right-of-way expansion capability.
Future increases in power delivery must go underground.

Ed Walsh (Westinghouse):

He again broached the topic of toxicity. He pointed out that
aluminum fluoride formed in arcs is a highly toxic material. He
wondered if anyone had ever been poisoned or otherwise adversely
affected by the arcing byproducts of an SF_6 system. The answer from
the utility's viewpoint seems to be no. He also expressed concern
about toxic contamination in substations due to rupture failures.

Mike Pohl (Air Products):

He mentioned that the recommended procedure for cleaning up fluoride
contaminated SF_6 is to dump the gas into a gas cart, preferably with
a blower. Technicians performing this task should leave no part of the
body exposed, e.g., they should have sleeves and pant legs taped, wear
gloves, gas masks, etc.

Loucas Christophorou (ORNL):

He pointed out that one desirable and promising feature of some new gas mixtures is that they may be more resistant to production of toxic gases in arcing. There is no doubt that this is an important feature deserving careful consideration. He also argued that one should look into scavenging techniques for removal of toxic byproducts.

Vasu Tahiliani (EPRI):

He mentioned that EPRI already has a project addressing this problem of developing scavenging techniques for toxic substances.

Martin Mastroianni (Allied Chemical):

Circuit breakers, he noted, have built-in gas cleaning systems. In a two pressure breaker, for example, there is an active system where the gas is pumped through a cleaning system in the breaker. In a single pressure breaker, there is a cleaning system on the side of the port to clean gas up from normal arcing operation. One of the goals of the EPRI project mentioned will be to look at how effective various cleaning agents are. Also, one must determine if there is sufficient cleaning capacity. In a transmission bus, the system is compartmentalized and gas can be cleaned, or scrubbed, by pumping it through a cart with a cleaning system. He pointed out that if a burn-through in a power line occurred, the release of toxic gas would only be for a short period, and it is unlikely, unless a worker is very close at the time of failure, that local toxicity would prevail and be maintained at hazardous levels for very long. Data on long term toxicity does not apply in this case. He also mentioned that there have thus far been no recorded human injuries or deaths due to exposure to SF_6 gas used in power systems. The major concern with

hazards from burn-throughs would be in enclosed gas insulated substations that have inadequate venting to prevent trapping of decomposed gas.

Jack Dutton (University College Swansea):

Turning to the academic perspective, he again emphasized that once all of the fundamental atomic and molecular collision processes are identified and understood and incorporated into a complete model, one does not have to measure every sparking potential to know how a given system (dielectric gas mixture) will behave. Better theoretical models are needed, and better models require better fundamental input data. As more reliable fundamental data become available, one can also hope to extend the range of the modeling effort to include other gases and other operating conditions. Considerable good basic data exist already for simple, common gases like H_2 and N_2, but the data is sparse for many of the various exotic fluorocarbon gases discussed in this workshop as dielectric additives or as possible replacements for SF_6. Extension of modeling will also require improved computation techniques. In considering nonuniform fields, modeling must also be linked with experiments on the growth of space charge. He recommended a basic experimental program on the study of space charge development. Particularly at high fields one also needs to know more about fundamentals of what happens at the interface between the gas and electrodes. Experiments are needed to look at microscopic details of what happens on a surface in a short time scale (say on the order of microseconds or less) in fields greater than 10^7 V/m at high gas pressures. It is his opinion that the technology does not yet exist that will allow satisfactory performance of these kinds of experiments, at least under conditions

that approximate practical situations. The collection and critical analysis of fundamental data are needed to support future modeling efforts. These data include collision cross sections and electron swarm coefficients. One critical output from modeling is the sparking potential. Again he posed the question concerning the need for critical evaluation of electrical breakdown data. Should one, for example, produce a handbook of critical data for gaseous dielectrics? Input from many different laboratories would, of course, be required to generate such a handbook.

N. Giao Trinh (IREQ):

He expressed the opinion that results of fundamental studies or theoretical models can never be a substitute for testing. The extrapolation of models which apply to ideal situations cannot be made easily to practical situations. Testing must always be relied on as the final method of determining acceptance of insulating systems. He questioned whether the results obtained from fundamental research can really be made applicable to engineering problems, and expressed the need to establish more of a link between basic and applied studies.

Jack Dutton (University College Swansea):

He agreed that one would never get to a situation where modeling based on fundamental physics could replace engineering testing. That is not the ultimate purpose of modeling. It should rather provide guidance in design of future high voltage systems and help determine which are the more promising systems that should be subjected to extensive testing.

Ara Chutjian (JPL):

He agreed that fundamental data and modeling can help in finding the best choices for gases to be tested. He noted that one of the present gaps in fundamental data was in the low electron energy region. Many cross sections and rate coefficients are not determined in the important energy region below 15 meV where, for example, attachment cross sections are rapidly increasing. He then proceeded to describe in some detail a new experimental method developed at JPL to measure line shapes for attachment of threshold electrons to electronegative gas molecules such as SF_6 and $CFCl_3$. With the technique described, it is now possible to measure attachment cross sections at electron energies in the range of 0-50 meV which is not covered in measurements by swarm techniques such as those used in the ORNL program. The technique involves the production of a narrow band of low energy electrons via direct photoionization of Xe gas to the $^2P_{1/2}$ state of Xe^+ in a field free region. The electronegative gas of interest is mixed in with Xe, and negative ions such as SF_6^- or Cl^- produced by attachment of the photoelectrons are detected with a mass spectrometer. The electron energies in the experiment are varied by changing the wavelength of the photon source. The photon source for these experiments is a discharge lamp with a monochromator. The measured production, P, of a negative ion, say X^- at an incident photon energy E_0 is obtained from the expression

$$P(E_0) = S * (\sigma_I \cdot \sigma_A)$$

where S is the incident photon bandwidth, σ_I and σ_A the Xe photoionization and electronegative gas electron attachment cross sections, respectively, and where * denotes convolution. The Xe photoionization cross section is assumed to have the usual step function behavior and the function S is taken to be a Gaussian with a width determined by the slit width (or resolution) of the monochromator. They have measured a width of 30 meV for the low energy electron attachment cross section in SF_6. They can put their measured attachment profiles on an absolute cross section scale by normalization to the results of "good" swarm measurements at electron energies above 100 meV. He noted that they can also look at dissociative attachment channels.

R. J. Van Brunt (NBS):

He commented that one of the purposes of the NBS swarm data evaluation program is to identify possible serious gaps in the fundamental data. An example of this was just pointed out in the discussion by Dr. Chutjian, namely that there is very little reliable cross section data at low electron energies. He also questioned where the emphasis in the modeling effort should be placed. Clearly some of the newer, exotic gas mixtures such as those involving perfluorocarbons are not yet ripe for modeling since very little fundamental cross section data are now available. Perhaps modeling efforts should concentrate more for now on the familiar gases and gas mixtures such as SF_6, SF_6-CO_2, SF_6-H_2, SF_6-N_2, and CO_2-N_2 for which considerable fundamental data exist, and where much yet remains to be done in understanding fundamental gas discharge phenomena. Eventually modeling can be extended to other

gases and mixtures as reliable swarm and cross section data for these
become available. He urged a vigorous experimental program to
obtain fundamental data on some of the newer, more promising electro-
negative gas additives to gaseous dielectrics. One should, for example,
try to obtain a fundamental understanding of why synergisms occur in some
cases but not in others, and why some mixtures work better than others.

Loucas Christophorou (ORNL):

He commented that they actually have measured cross sections down
to zero energy, although indeed in their swarm measurements the cross
sections derived from attachment rates are quite uncertain for energies
below $(3/2)kT$ (~ 0.038 eV). He questioned the importance of knowing
exact values for these very low energy cross sections in understanding
the electrical behavior of a gaseous dielectric, since the relative number
of electrons at very low energies (at the low energy tail of the
distribution) is very small. He commented further about the disturbing
fact that there is not a single laboratory in the world today doing
D/μ (diffusion/mobility) measurements. He also pointed out that although
there are many laboratories performing measurements of relative cross
sections, there are only a few doing the more important absolute cross
section measurements. Of course, absolute cross section measurements
are more difficult to make. However, absolute cross sections are needed,
particularly in the subexcitation energy range.

Jack Dutton (University College Swansea):

He agreed that there is a lack of effort on D/μ measurements.
However, he noted that the situation is more serious than that since we
cannot at this time measure attachment and detachment coefficients to
better than 50% except in very special cases.

Bob Hebner (NBS):

He brought up the question about where the effort in
modeling should be placed. He pointed out that modeling programs are
underway to predict reliability of gas insulated <u>systems</u>, and the important
considerations here are not necessarily processes that occur in the gas
itself, but rather such things as particle dynamics, exchange of electronic
charges at metal-particle interfaces, etc.

R. J. Van Brunt (NBS):

In reply to this comment, he argued that there are two different
points of view, one being that of evaluating the dielectric performance
of a gas by itself for comparison purposes, and the other being that
of evaluating total system performance. Most of the discussion at
this workshop has focused on consideration of the gas by itself, such
as its breakdown strength or its interaction with other materials.
There is the prevailing understanding nevertheless that this is far
from the complete picture, and in a practical system there may be
many other more important things going on that one should consider.

Jack Dutton (University College Swansea):

He emphasized again that one needs guidance about the behavior
of the gas. The effects of particles and surfaces can in fact be
viewed as part of the gas problem.

Roy Nakata (GE):

He expressed the opinion that when considering the question of
a gas system versus a practical system one should distinguish between
the point of view of near and long range future. Although there is a
definite need for information on fundamental behavior of gases for the

future, there are anomalous behaviors in complete practical systems that need examination now. For example, there are questions in considering electrodes or conductors of how sharp is "sharp", and how divergent is a "divergent" field. Whereas in a gas transmission line the field may be easy to determine, in a transformer this is not necessarily the case. Should we not design systems in the near future to take better advantage of gases at hand? Use could perhaps be made of new materials and corona stabilization.

Jack Dutton (University College Swansea):

He noted that corona stabilization depends entirely on the development of space charge, and consequently if one can acquire a basic understanding of space charge development, then one can get a handle on the problem of corona stabilization.

Martin Mastroianni (Allied Chemical):

He felt that the concern of this workshop is with future electrical systems. For electric power systems, there are the needs of three general types of equipment, namely (1) transmission lines, (2) circuit breakers, and (3) transformers. For a circuit breaker, the important characteristic of the gas dielectric used is its arc interrupting capabilities, and for this application, the insulating properties are of secondary importance. For a transformer, the heat transfer properties of the gas are important. In a GIT line the breakdown voltage or insulating quality takes precedence. The point again is that the type of gaseous dielectric used should depend on application and equipment requirements. There is still much that remains unknown about the electrical properties of SF_6, and as a result we presently design equipment that can use only

50% or less of the intrinsic dielectric strength capability of this gas. He is of the opinion that emphasis for future research should address the problem of particles. If a gas is found that has an equal or higher dielectric strength than SF_6 or other gas presently used, it must be demonstrated that this remains true for conditions of particle contamination or particle initiated breakdown. He expressed the need for more fundamental work on the breakdown problem, in particular the investigation of mechanisms that prevent optimum use of the intrinsic strength of the gas. Attempts should be made to look at a gas mixture from the point of view of adding a new kind of "magic fairy dust" that will enable one to use the full capability of the gas.

Roy Wootton (Westinghouse):

He brought up again the question of the benefits of corona stabilization mentioned by Roy Nakata. Corona stabilization occurs, for example, on the tip of a particle or surface protrusion. However, if an initiating electron does not appear early on, corona stabilization will not happen under impulse, whereas a later initiating electron will lead to breakdown. The delay in an initiating electron is thus of no benefit in a nonuniform field regime where one is relying on corona stabilization to prevent breakdown. He expressed the need to look at a practical system as a "whole" system. In considering aging one must not only look at the chemistry that goes on in the gas but also interaction between the gas and the resin. Also, resins at high temperature undergo deterioration and give off their own gases. In the short term, it appears that it would be desirable to learn more about what goes on

in SF_6 so that its full potential as a dielectric can be utilized.
A case can be made that flashover on solid insulators in compressed
gas systems deserves priority in future research. In the long term,
one has to look more carefully at the basic data for gases.

Jack Dutton (University College Swansea):

The question of preconditioning of high voltage compressed gas
insulated apparatus was raised by several including Alexander Stewart
of Harry Diamond Labs. In response to this, Dr. Dutton pointed out that
although the conditioning effect is well known, it is not necessarily
well understood. For example, in some systems a polished electrode
surface can become pitted as a result of conditioning, yet the overall
dielectric strength of the system improves. Why does this happen?

Chat Cooke (MIT):

He pointed out that as systems are pushed to higher and higher
stresses one is less and less able to predict and understand insulation
performance. The predictions become less capable of meeting reality.
When looking for a "better" gas dielectric one is trying to meaningfully
compare the electrical performances of various gases. Chat proposed
that serious consideration be given to a standardization of electrodes
for testing with the objective that meaningful comparisons can be made
of different gases. The electrodes will have to be special because
it is no longer possible to consider uniform field conditions, since surfaces
are in general nonuniform. Many tests have shown that if one produces
spark breakdown between electrodes in different gases, the resulting
physical surfaces of these electrodes can be quite different. The nature
of electrode surfaces changes completely as a result of breakdown and
this change is dependent on the gas used. He would like the electrodes

used to be useful from a calculational point of view. As one suggestion,
he proposed that one use an electrode system in which there is a known,
well defined, small asperity on the cathode surface. This asperity should
be defined so that the initial field distribution is well characterized.
Such a protrusion could have a spherical end radius and a height-to-radius
ratio less than ten. The electric field for a hemispherical protrusion or
sphere on a pedestal can be solved exactly. In comparing gases, one
should look at the initiation or inception of breakdown. He suggested
that the partial discharge study carried out at NBS by Van Brunt is
perhaps a useful approach. He emphasized that the "standard" electrode
system chosen should be a compromise of some kind in which it is possible
to make calculations and yet will allow one to make the leap to prediction
of what might happen in practical systems. The cell must be small enough
so that it can be used readily, but have the characteristics that enable
one to infer what might happen in a practical system. Of course, there
is really no hope of using such a laboratory test to predict exactly what
will happen in a big practical system. However, it can serve as a basis
for a better, more meaningful comparison of the proposed insulating
materials, namely the gases, and provide information that is related as
best possible to a practical condition. In any case, it should not be
designed to give misleading information.

Bruce Bernstein (EPRI):

He suggested that this question of standardized electrodes be fed to
the forthcoming International Symposium on Gaseous Dielectrics. He also
indicated that he would alert (and has in fact already done so)
Dr. Alan Cookson, chairman of the "Insulation Systems for Gas Insulated
Cables" Subcommittee (5-12) of the Insulated Conductors Committee about

this problem with hopes that it be considered at the next subcommittee
meeting.

R. J. Van Brunt (NBS):

He expressed sympathy for the need to develop standardized
electrodes for testing and indicated the interest of NBS in this effort.
He reminded the group that it is the function of NBS to assist industry
in development of more meaningful test, monitoring and measurement
procedures. Although they are not in the business of developing new
materials, namely in this case gaseous dielectrics, they take the view
that a better understanding of basic physical phenomena can help not only
in the development of new materials but also in development of more
meaningful comparative tests of these materials. They have recently
concentrated their laboratory effort on the study of partial discharge
(corona) phenomena with the hope that observation of prebreakdown partial
discharges in nonuniform fields might offer a better way of evaluating
relative dielectric performance of different gases. He raised the question
about the urgency of the need for new gaseous dielectrics in all
applications. He could see, for example, an urgent need in the specialized
case of high power switching, as used for large lasers and beam machines,
where gas decomposition is significant, but the urgency of the need in
electric power transmission applications was not entirely clear. Perhaps
more could yet be done with existing gases.

Ara Chutjian (JPL):

He raised the question about possible effects of fluorocarbons used
in dielectrics on the ozone layer in the earth's upper atmosphere.

Loucas Christophorou (ORNL):

In response to Van Brunt's question, he expressed the opinion that there is a need that must be satisfied now for new gaseous dielectrics in power systems application. Industry should, for example, be able to adjust itself to new dielectrics and consider design of equipment to accommodate different kinds of gases. One should not strive now for the optimum systems. Optimization of systems will naturally occur as need arises and as more scientific information is acquired about behavior of materials.

Roy Wootton (Westinghouse):

Going back to Dr. Cooke's proposal for standardized electrodes, he indicated that in their EPRI program to examine new gases they also encountered the difficulty mentioned, namely that comparative breakdown tests on 1 atm and 4 atm gases in uniform fields did not necessarily give a good indication of what happens for tests performed using geometries that simulate practical conditions.

Dr. V. L. Kenyon, III (Naval Surface Weapons Center):

He brought up the problems associated with the special application of a gaseous dielectric as a high power switching medium. The big problems here are how to avoid total decomposition of the gas and limit the deleterious effects of the decomposition products on the rest of the switch. He pointed out that this use of gaseous dielectrics, although not particularly significant now, can be expected to increase in the future.

Bruce Bernstein (EPRI):

He commented that EPRI has made a conscious effort to avoid funding research on SF_6-N_2 mixtures, since considerable work on this has been conducted by others.

Vasu Tahiliani (EPRI):

He argued that one of the challenges for the future is to devise ways of exciting the insulation system to screen out particular defects like particles, protrusions, broken insulators, absence of gas, presence of air, etc., without having to apply high voltage. EPRI is currently interested in funding research directed to this problem.

Dave Miller (Gould-Brown Boveri):

He wondered if modelers and those involved with design of measurements are going in the direction that will help those designing equipment decide why they may, for example, be achieving only a fraction of the total insulating capability of a gas, such as is the well known case for SF_6 discussed several times in this workshop. He expressed concern that those doing basic gas studies are going in the direction of controlled experiments which do not readily relate to practical situations. Perhaps one needs to steer modeling more in the direction that makes it applicable to practical equipment. Should there not be a number of different models, e.g., models that consider separately particle effects, breakdown along insulator surfaces, etc.?

Jack Dutton (University College Swansea):

In reply to Dr. Miller, he emphasized again that in the case of SF_6 something other than the gas dominates the breakdown condition at high fields and high pressures. In this situation, one is injecting a lot of electrons from a small site somewhere in the system. The question then is, can one model a situation in which one injects a space charge over a very small volume? At present, this is a difficult situation to model, but some progress is being made.

Loucas Christophorou (ORNL):

He pointed out that a large number of experiments and tests under controlled conditions are needed to supplement modeling. They are, for example, investigating under controlled conditions effects of surface roughness, particles, etc. These kinds of investigations as well as modeling are required before it is advisable to proceed with any large scale industrial testing. There might be some questions, however, concerning the appropriate types of tests to which new gases should be subjected.

R. J. Van Brunt (NBS):

He commented that the fundamental work primarily provides guidance and does not solve immediate problems associated with practical systems. He cited the example of Castonquay's work on effects of contamination on rate of gas degradation. A fundamental understanding of the chemistry involved here could help in the design of gaseous insulation which is resistant to contamination. The fundamental research often works around the fringes of the practical problems, and benefits of this work may not be realized until long after the work is completed. It is his opinion that basic research should be viewed in general as being geared more toward long range, future technology and adding to the store of knowledge upon which those in the future can draw in designing better systems. It may, nevertheless, provide insight into the solution of existing problems, but should not necessarily be steered in that direction. Modeling and basic laboratory tests and measurements will never be a substitute for engineering testing; on the other hand engineering testing alone cannot provide the insight acquired from basic research.

Loucas Christophorou (ORNL):

In closing this workshop, he made an announcement concerning the forthcoming Second International Symposium on Gaseous Dielectrics that will be held at the Hyatt Regency Hotel, Knoxville, Tennessee, March 9-13, 1980. It will be hosted by the Oak Ridge National Laboratory and sponsored by the Department of Energy in cooperation with the IEEE Power Engineering Society. Those who have not been notified of this meeting and want to attend should contact:

> Dr. L. G. Christophorou
> Chairman, Second International Symposium
>   on Gaseous Dielectrics
> Oak Ridge National Laboratory
> Building 4500S, H-162
> P.O. Box X
> Oak Ridge, Tennessee 37830 .

It is hoped that questions, ideas, and opinions generated at this workshop will be brought to the symposium for further discussion. Again, the symposium will bring together those from many countries involved in a broad spectrum of research from basic physics to applied engineering.

AGENDA

WORKSHOP ON GASEOUS DIELECTRICS FOR USE IN FUTURE ELECTRIC-POWER SYSTEMS

National Bureau of Standards
Gaithersburg, Maryland

September 10 and 11, 1979

Monday, September 10 -- Lecture Room D, Administration Building (101)

11:00 am -- Registration

1:00 pm -- Chairman's Opening Address
T. F. Garrity, Department of Energy

1:15 pm -- Users Look at Insulation Systems
D. E. Massey, GPU Service Corporation

1:30 pm -- An Experimental Study of Dielectric Gases for Practical Aoolications
R. E. Wootton, Westinghouse R&D Center

2:00 pm -- Breakdown and Stability Properties of Some New Gaseous Dielectrics
M. J. Mastroianni, Allied Chemical Corporation

2:30 pm -- Calculation of Vaoor Pressure for Dielectric Gas Mixtures
M. R. Kegelman, E.I. duPont de Nemours & Company

3:00 pm -- Coffee

3:30 pm -- The Oak Ridge Program on Gaseous Dielectrics
L. G. Christophorou, Oak Ridge National Laboratory

4:00 pm -- Analysis of Trace Decomposition Products in Gaseous Dielectrics
J. Castonquay, Hydro-Quebec Institute of Research

4:30 pm -- Study of Corona Characteristics and Corona Chemistry in
Gaseous Dielectrics
R. J. Van Brunt, National Bureau of Standards

Tuesday, September 11 -- Room A340, Metrology Building (220)

8:30 am -- Registration

9:00 am -- Basic Factors Influencing Reliability
C. M. Cooke, Massachusetts Institute of Technology

9:30 am -- Swarm and Breakdown Data for Gaseous Dielectrics
J. Dutton, University College of Swansea

10:00 am -- Coffee

10:30 am -- Panel Discussion -- Needs for Future Research
Chairman - B. Bernstein, EPRI

Panel Members - J. Dutton, J. Castonquay, D. E. Massey,
M. J. Mastroianni, R. J. Van Brunt,
and J. Beehler

1:30 pm -- Lunch - provided for participants in the NBS Senior Lunch Club

2:30 pm -- NBS Openhouse -- Gaseous and Liquid Dielectrics Research
Laboratories

Workshop on Gaseous Dielectrics for Use In Future Electric-Power Systems

National Bureau of Standards
September 10 and 11, 1979

1. Earl C. Beaty
    JILA Atomic Collisions Information Cntr.
    Joint Institute for Laboratory Astrophysics
    National Bureau of Standards and
       University of Colorado
    Boulder, CO 80309

2. Bruce S. Bernstein
    Electric Power Research Institute
    1800 Massachusetts Avenue, N.W.
    Suite 700
    Washington, D.C. 20036

3. Jacques Castonquay
    Science des Materiaux
    Institute de Recherche de l' Hydro-Quebec
    1800 Montee' Ste-Julie
    Varennes, Quebec
    Canada

4. Loucas G. Christophorou
    Atomic, Molecular and High Voltage Physics
       Laboratory
    Oak Ridge National Laboratory
    P.O. Box X
    Oak Ridge, TN 37830

5. Ara Chutjian
    Jet Propulsion Laboratory
    California Institute of Technology
    4800 Oak Drive
    Pasadena, CA 91183

6. Chatham M. Cooke
    High Voltage Research Laboratory
    Building N-10
    Massachusetts Institute of Technology
    Cambridge, MA 02139

7. D. Ken Davies
    Research and Development Cntr.
    Westinghouse Electric Corp.
    Beulah Road
    Pittsburgh, PA 15235

8. John Devins
    Room 21, Radiation Bldg.
    General Electric Company
    River Road
    Schenectady, NY 12301

9. Jack Dutton
    Department of Physics
    University College Swansea
    Swansea, Wales
    Great Britain

10. Thomas F. Garrity
    Electric Energy Systems Division
    Department of Energy
    20 Massachusetts Avenue, N.W.
    Washington, D.C. 20545

11. Robert E. Hebner
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

12. David R. James
    Atomic, Molecular and High Voltage
       Physics Laboratory
    Oak Ridge National Laboratory
    P.O. Box X
    Oak Ridge, TN 37830

13. Philip E. Jones
    Allied Chemical
    Specialty Chemicals Division
    20 Peabody Street
    Buffalo, NY 14210

14. Matthew R. Kegelman
    E.I. DuPont de Nemours and Co.
    Petrochemicals Department
    Bldg. 136, Room 139
    Experimental Station
    Wilmington, DE 19898

15. Edward F. Kelley
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

16. William Kennedy
    Transformer Department
    General Electric Company
    100 Woodlawn Ave.
    Pittsfield, MA 01201

17. Van Kenyon III
    Naval Surface Weapons Cntr.
    White Oak Laboratory
    Silver Spring, MD 20910

18. David A. Leep
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

19. Dave Massey
    GPU Service Corp.
    Route 183, Reed Road
    Box 1018
    Reading, PA 19603

20. Martin J. Mastroianni
    Allied Chemical
    Specialty Chemicals Division
    20 Peabody Street
    Buffalo, NY 14210

21. Ronald H. McKnight
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

22. J. Robert McLoughlin
    General Electric Company
    Research and Development
    Room 12, Radiation Bldg, K1
    P.O. Box 8
    Schenectady, NY 12301

23. David B. Miller
    Gould-Brown Boveri
    Research and Development Division
    Norristown Rd. and Route 309
    Spring House, PA 19477

24. Martin Misakian
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

25. John H. Moore
    Department of Chemistry
    University of Maryland
    College Park, MD 20742

26. Roy Nakata
    Bldg. 9, Room 110, HVL
    General Electric Company
    100 Woodlawn Avenue
    Pittsfield, MA 01201

27. Robert N. Noberini
    Consolidated Edison Co.
    4 Irving Place
    New York, NY 10003

28. Oskars Petersons
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

29. Michael C. Pohl
    Air Products and Chemicals, Inc.
    Specialty Gas Department
    Box 351
    Route 1
    Tamaqua, PA 18252

30. A. H. Qureshi
    Department of Electrical Engineering
    University of Windsor
    Windsor, Ontario N9B 3P4
    Canada

31. John D. Ramboz
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

32. I. Sauers
    Atomic, Molecular and High Voltage
      Physics Laboratory
    Oak Ridge National Laboratory
    P.O. Box X
    Oak Ridge, TN 37830

33. Alexander L. Stewart
    Harry Diamond Labs
    2800 Powder Mill
    Aurora Facility
    Adelphi, MD 20783

34. Vasu Tahiliani
    Electric Power Research Institute
    3412 Hillview Avenue
    P.O. Box 10412
    Palo Alto, CA 94303

35. N. Grao Trinh
    Institute de Recherche de l' Hydro-Quebec
    1800 Montee' Ste-Julie
    Varennes, Quebec
    Canada

36. Richard J. Van Brunt
    National Bureau of Standards
    Electrosystems Division
    Washington, D.C. 20234

37. A. P. Vitols
    General Electric Co.
    100 Woodlawn Avenue
    Pittsfield, MA 01201

38. Edward J. Walsh
    Westinghouse Electric Corp.
    Sharon, PA 16146

39. Roy E. Wootton
    High Voltage and Gas Physics
    Westinghouse Research and Development
       Center
    Beulah Road
    Pittsburgh, PA 15235

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Electric Power Research Institute, 3412 Hillview Ave.,
P.O. Box 10412, Palo Alto, California 94303
Department of Energy, 20 Massachusetts Ave., Washington, DC 20545
National Bureau of Standards, Washington, D.C. 20234

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This workshop was held at the National Bureau of Standards laboratories in
Gaithersburg, Maryland, on September 10-11, 1979. The agenda and a list of active
participants is attached. The workshop was organized for the purpose of addressing
questions concerning current and planned research on development of new gaseous
dielectrics viewed as possible substitutes for SF_6. Focus was on identifying
technological barriers to use of new gases and gas mixtures and questions concerning
properties of gases in need of further investigation. It brought together many
individuals from industry, government, and academia with diverse interests and
opinions concerning the needs for future research in the gaseous dielectrics area.
It was assumed that the workshop would provide a stimulating prelude to the forth-
coming International Symposium on Gaseous Dielectrics where unresolved questions
concerning the needs and desirable directions of future research can again be debated.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Basic and applied research; chemical stability; corona; dielectric strength;
electric power systems; gaseous dielectrics; insulation; SF_6; sulfur hexafluoride;
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